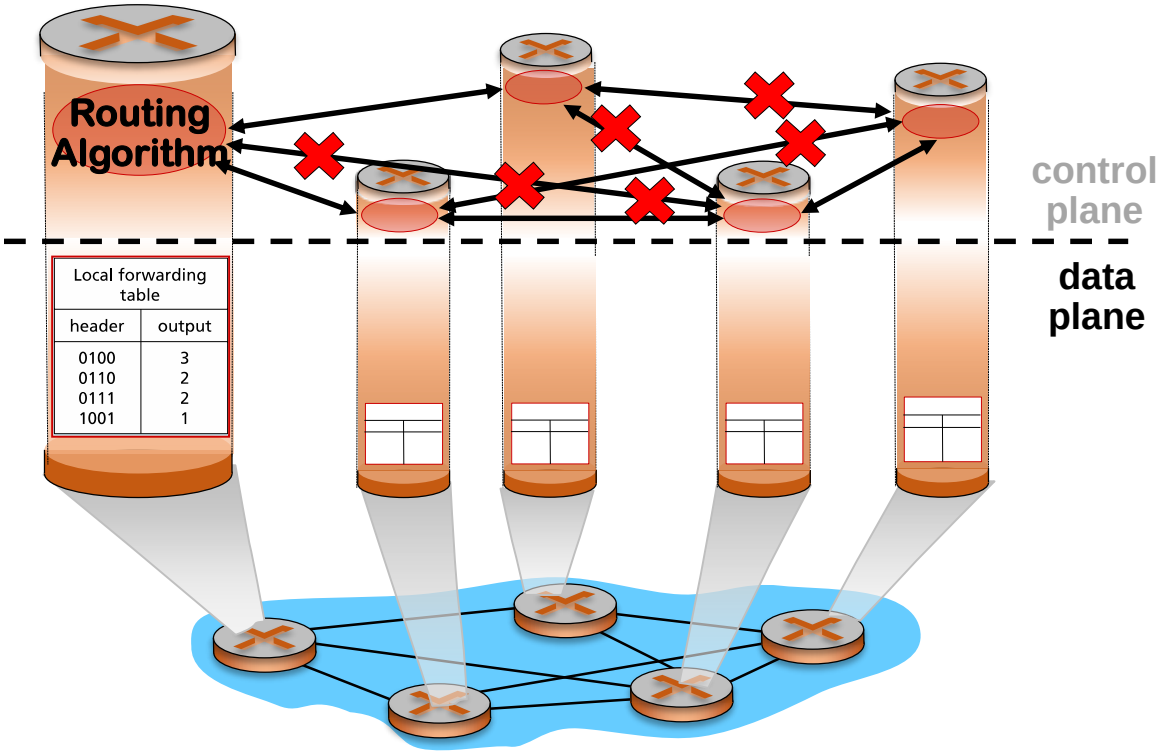
Fast Rerouting Against Dynamic Failures: 2-Resilience via Ear-Decomposition and Planarity

Wenkai Dai (TU Berlin, Germany & University of Vienna, Austria), Klaus-Tycho Foerster (TU Dortmund, Germany), and Stefan Schmid (TU Berlin, Germany)

Motivation: Handling Link-Failures on Control-Plane Is Slow

- Link failures are unavoidable so mechanism to route around
- Traditionally, control-plane handles link failures by recomputing routing tables (e.g., OSPF)
- Slow, unacceptable for critical applications



(Credits: Stefan Schmid)

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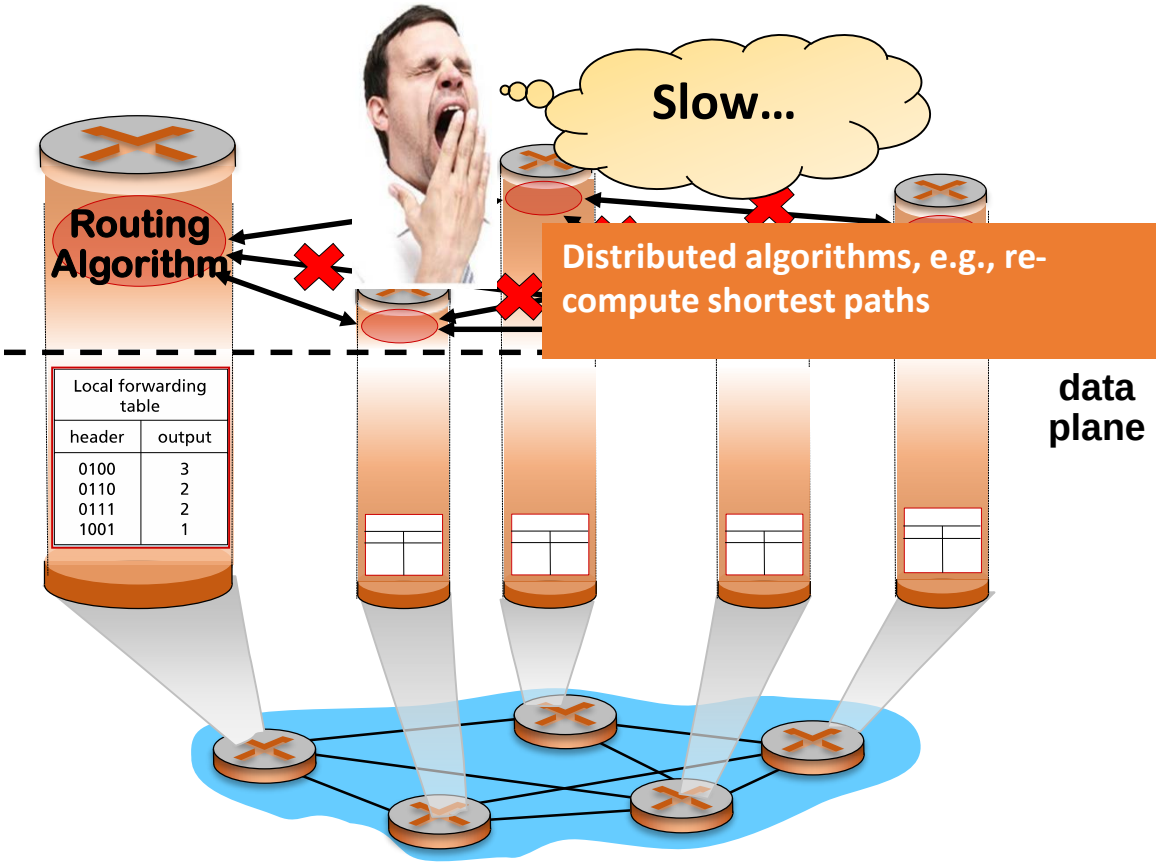
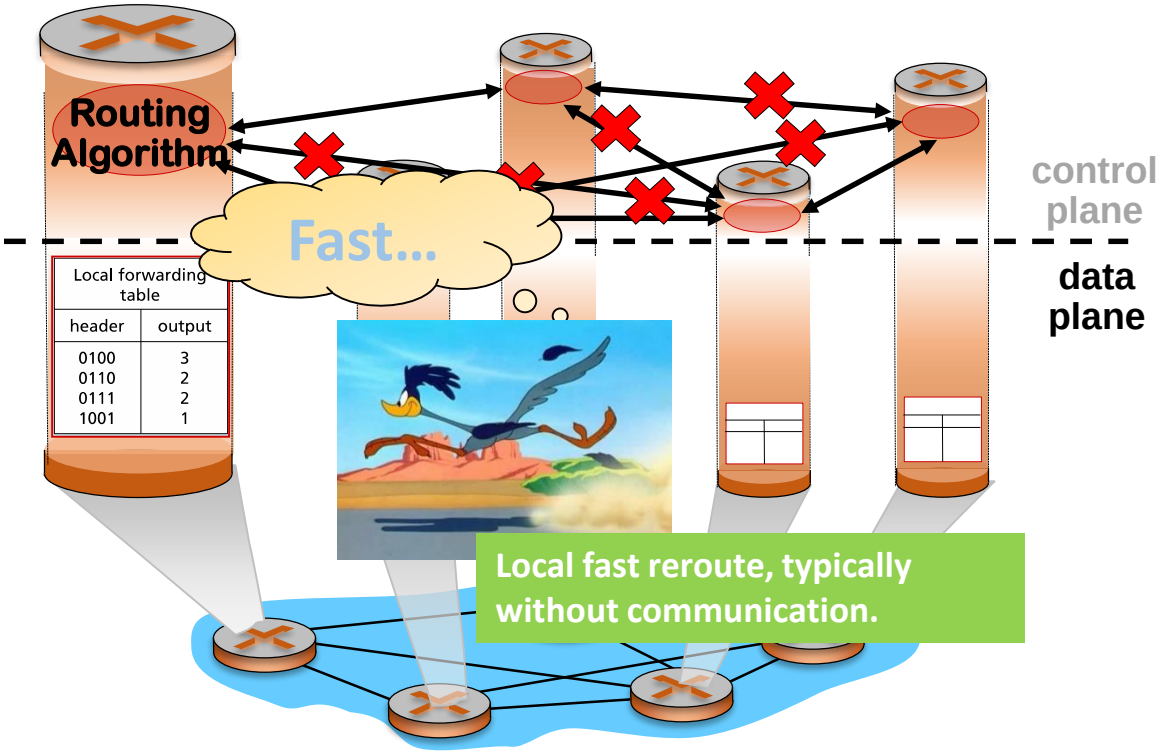


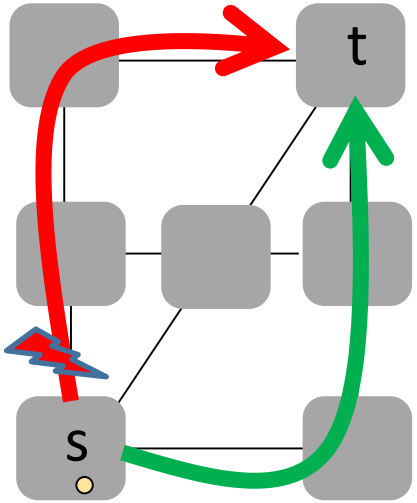
Motivation: Handling Link-Failures on Control-Plane Is Slow

- Fast reroute (FRR) on data-plane handles failures locally



Fast Rerouting (FRR) on Data-Plane

- Local failover without invoking control plane, by pre-installing alternative paths
- Conditional forwarding rules, only depending on local failures, no information about failures downstream
- Challenge: How to determine these pre-installing reroute rules

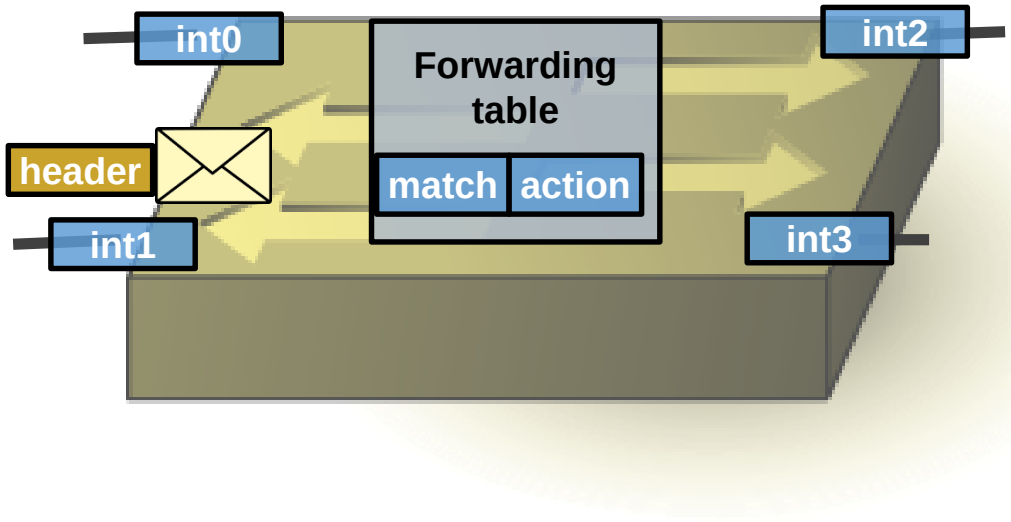


Introducing many algorithmic problems

Preinstalled, conditional failover rule, depending *only on local information*

Basic Routing Functions Only Use Local Information

- Network is a connected undirected graph $G=(V,E)$
- Packet forwarding can be model as a function



Basic Routing Functions Only Use Local Information

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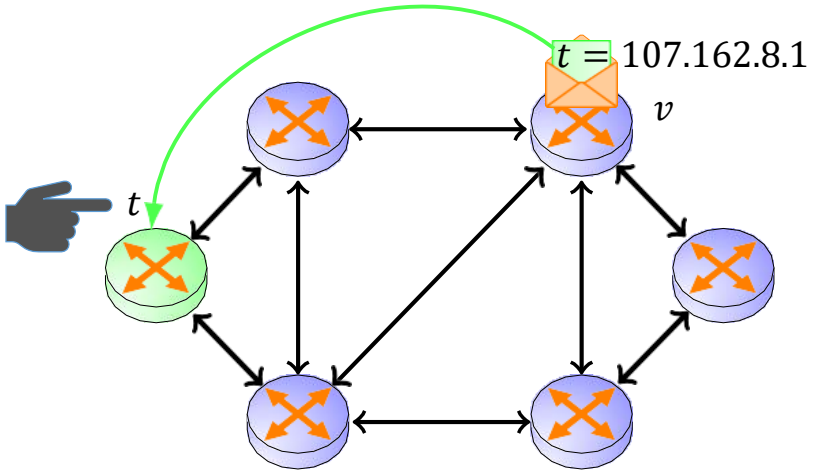
  - Destination t



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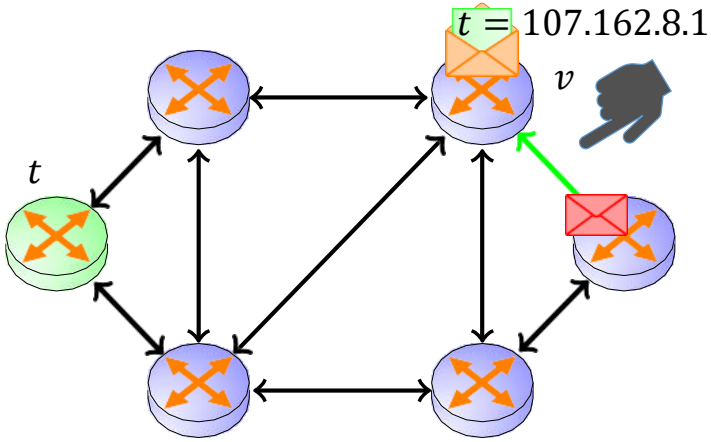

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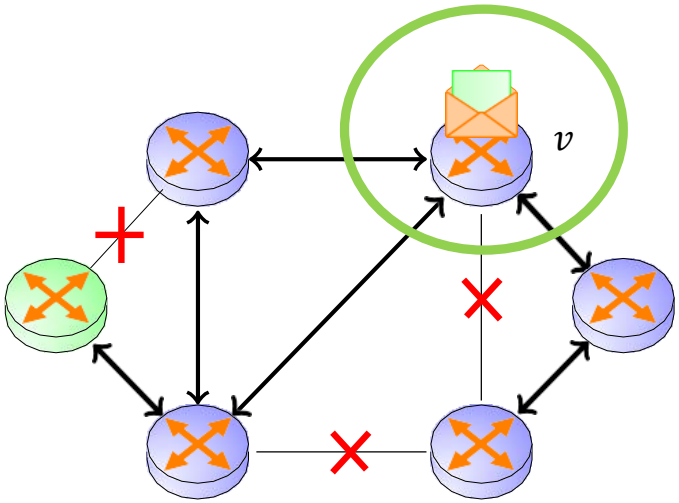

Basic Routing Functions Only Use Local Information

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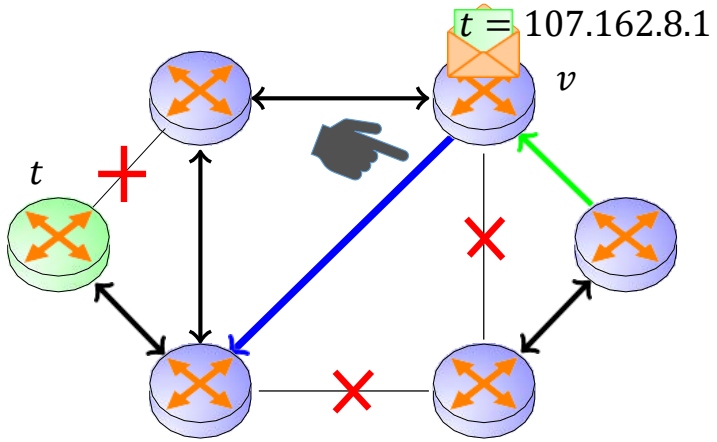
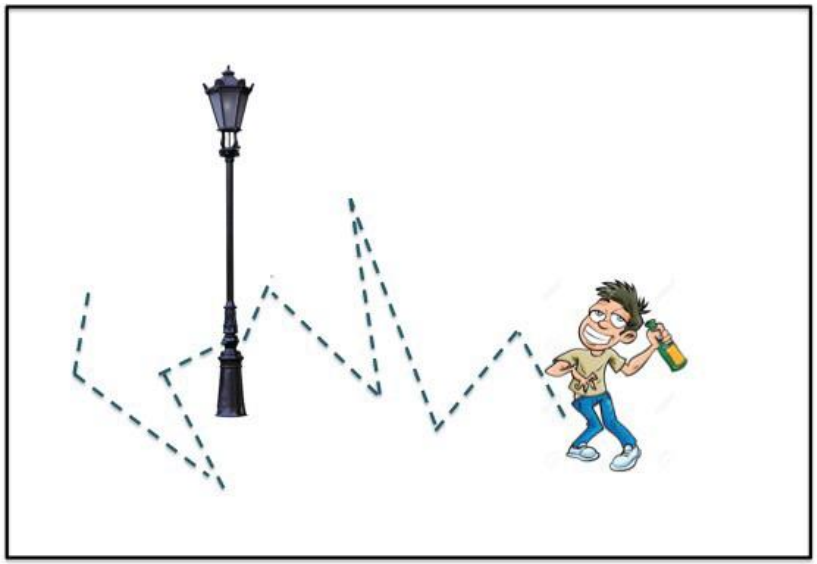
- **Basic** routing function at node v may only match on:
  - Destination t
  - Incoming port from $E(v) \cup \{\perp\}$
  - Incident edge failures $F \cap E(v)$
- To determine an outgoing link in $E(v) - F$
- We know, e.g., how to achieve 1-resilience [Kwong et al. 2011], [Feigenbaum et al. 2012]



Our Focus: Deterministic Forwarding Rules

- Only consider **deterministic** routing functions
- Randomized routing cons:
  - packet recording
  - long paths?
  - device limitations



Spectrum of Models

Basic Routing

Incident links | Per destination | Incoming port → Routing Function → Outgoing port

Source-matched Routing

Per source | Incident links | Per destination | Incoming port → Routing Function → Outgoing port

Optional: Header Bit-rewriting

Packet header rewritable-bits | Inputs of above routing, e.g., basic → Routing Function → Outgoing port | Packet header rewritable-bits

Spectrum of Models

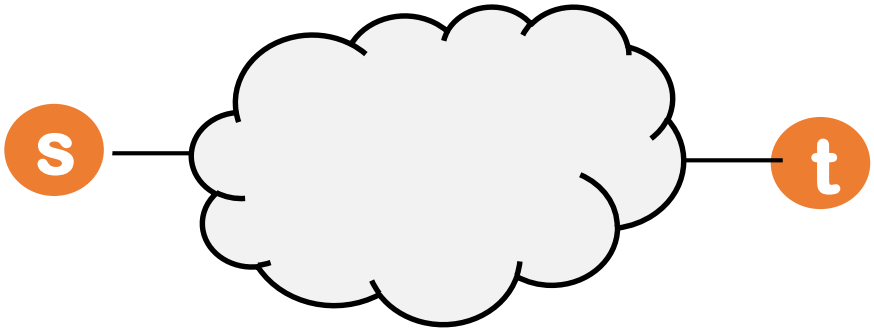
- **The more we match, the larger the tables**
- **Source-matched: $O(n^2)$ (for source and destinations), times failure scenarios (?)**
- **Bits-rewriting: even more overheads (and where to write in header?)**

Problem: Computing a k-Resilient Routing Scheme

- Given an undirected graph $G=(V,E)$ and a destination $t \in V$
- A routing scheme is called k-Resilient ($1 \leq k \leq |E|$) :
  - if any $v \in V$ can reach a destination $t \in V$ as long as $v-t$ still connected in $G-F$, for k **arbitrary link failures** $F \subseteq E(G)$
- Goal: Compute a k-resilient routing scheme for given $G=(V,E)$, $t \in V$ and k

The Model Matters

- Assume k-connected graph: how to tolerate k-1 failures?
- If I can match source, inport and destination?



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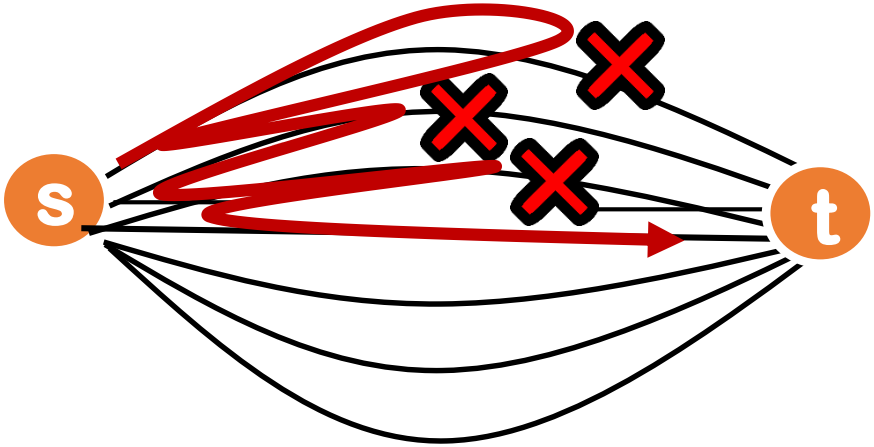

- Try one path after the other!

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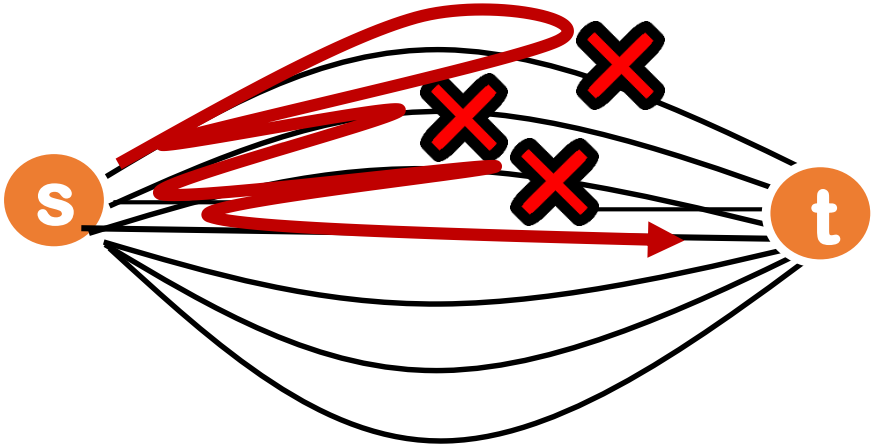

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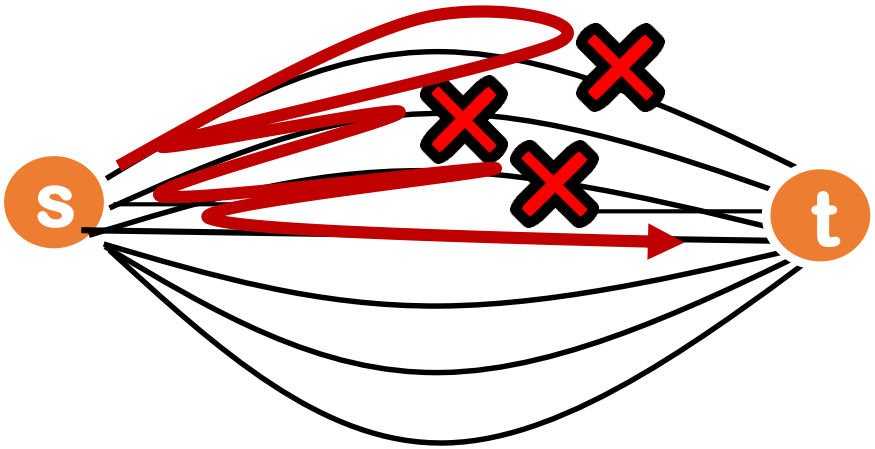

- Long-standing conjecture (that it still works)!

Related Works (Static Link Failures)

- Fast failover is a widely studied area, see recent survey
  - Chiesa et al. (2021): *A Survey of Fast Recovery Mechanisms in Packet-Switched Networks*
- Source-matched routing
  - Latest result: *Dai et al. (SPAA' 23): A Tight Characterization of Fast Failover Routing: Resiliency to Two Link Failures is Possible*

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A Survey of Fast-Recovery Mechanisms in Packet-Switched Networks

Marco Chiesa, Andrzej Kamisiński, Jacek Rak, *Senior Member, IEEE*, Gábor Rétvári, and Stefan Schmid

***Abstract*—In order to meet their stringent dependability requirements, most modern packet-switched communication networks support fast-recovery mechanisms in the data plane. While reactions to failures in the data plane can be significantly faster compared to control plane mechanisms, implementing fast recovery in the data plane is challenging, and has recently received much attention in the literature. This survey presents a systematic, tutorial-like overview of packet-based fast-recovery mechanisms in the data plane, focusing on *concepts* but structured around different networking technologies, from traditional link-layer and IP-based mechanisms, over BGP and MPLS to emerging software-defined networks and programmable data planes. We examine the evolution of fast-recovery standards and mechanisms over time, and identify and discuss the fundamental principles and algorithms underlying different mechanisms. We then present a taxonomy of the state of the art, summarize the main lessons learned, and propose a few concrete future directions.**

***Index Terms*—Fast reroute, network resilience, data plane.**

I. Introduction

PACKET-SWITCHED communication networks (datacen-

of the communication infrastructure. Over the last years, several network issues were reported that led to major Internet outages in Asia [1], resulted in huge losses in revenues [2], affected thousands of airline passengers [3], or even disrupted the emergency network [4]. Many applications already suffer from small delays: A 2017 Akamai study shows that every 100 millisecond delay in website load time can lead to a significant drop in sales [5], and voice communication has a tolerable delay of less than 150 ms; for games it is often less than 80 ms [6].

In order to meet their stringent dependability requirements, communication networks need to be able to deal with *failures* which are becoming more likely with increasing network scale [7]. Today, link failures are by far the most frequent failures in a network [8], [9], and handling failures is a fundamental task of any routing scheme.

This paper focuses on packet-switched networks, where resilience to failures on the network layer can either be implemented in the so-called *control plane* or in thee so-called the *data plane*. In a nutshell, the control plane relies on

The Model of Static Link Failure Is Unrealistic

- Previous research considers ***static*** link failures, i.e.,
  - **Simultaneous** and **permanent** (*unrecoverable*) Failures

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Reality:

- **Links fail *over the time***
- **And can recover!**

P. Gill et al. Understanding network failures in data centers: measurement, analysis, and implications (Sigcomm), 2011.

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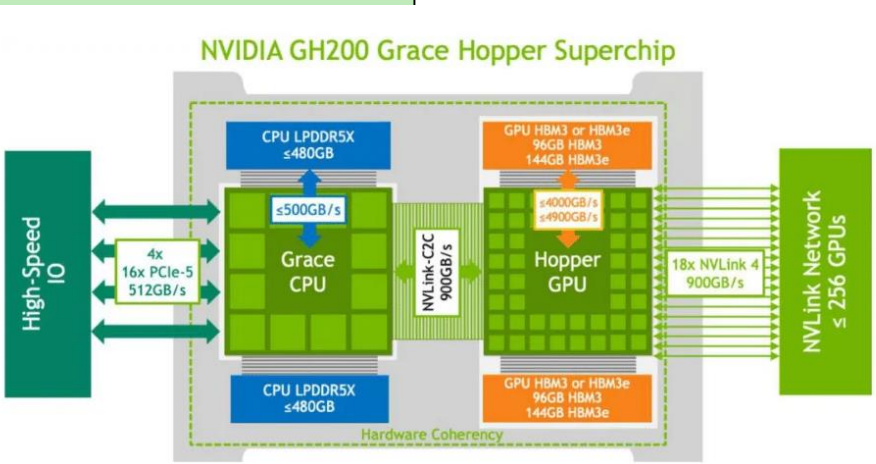
E.g., NVLink vs Copper



The Novel Models for Link Failures

Challenges: devise failover reroute rules on dynamic graphs?

Semi-Dynamic Link Failure

Links F fail *non-simultaneously*, but *still permanently.*

Dynamic Link Failure

Links F fail *non-simultaneously*, and *non-permanently.*

First insights: Dai et al. On the Resilience of Fast Failover Routing Against Dynamic Link Failures (IFIP Networking), 2025.

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Algorithm that works for semi-dynamic also works for dynamic!

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Related Previous Results and Our Main Contributions

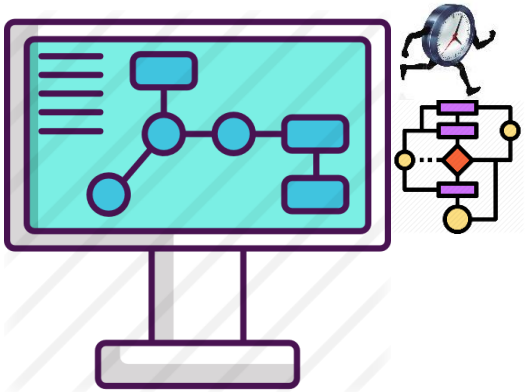
Failure type	Per-destination	Per source	Incoming port	Incident links	k-edge-connected graph	Graph Restrictions	Packet rewriting bits	Resiliency	Ref.
static	X		X	X	$k = 2$	planar		No 2-resilient	[Chiesa et al. 2016]
static	X	X	X	X		general		No 3−resilient	[Dai et al. 2023]
static	X	X	X	X		general		≤ 2-resilient	[Dai et al. 2023]
static	X		X	X		general	1 bit	≥ 2-resilient?	**Open**
static	X	X	X	X		general		≥ 2-resilient?	**Open**
dynamic	X		X	X	$k = 2$	planar	0	No 2−resilient	[This Talk]
dynamic	X		X	X		general	$\log k$	No k−resilient	[This Talk]
dynamic	X		X	X		planar	1 or 2	≤ 2-resilient	[This Talk]

Previous results

Our results

In particular:

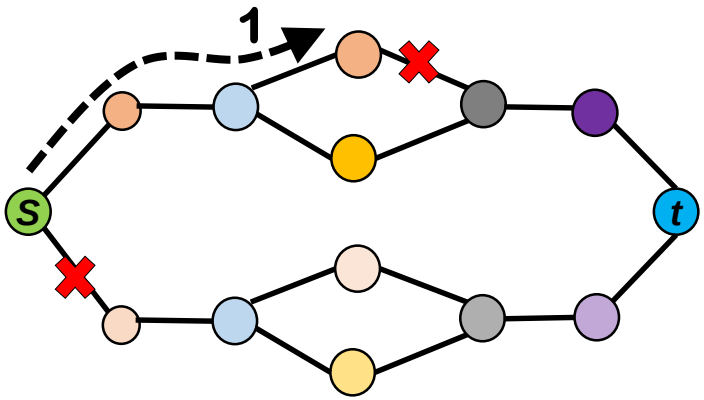
- A $\mathbf{2}$-resilient **basic** routing scheme against **dynamic** failures by **rewriting 1-bit** (**tight**) on **planar** graphs, **computable** within $O(n+m)$ per destination



- A $\mathbf{2}$-resilient **source-matched** routing against **dynamic** failures on **planar** graphs **without** rewriting is **impossible**

Impossibility: Via Case Distinction

- **Impossible** to have **2-resilient *source-matched routing*** against **dynamic failures *without rewriting bits*** **even on planar graph**
  - In the example, every node must use **link-circular routing** (clockwise or counter-clockwise)
  - Depending on order, fail dynamically: *indistinguishable*



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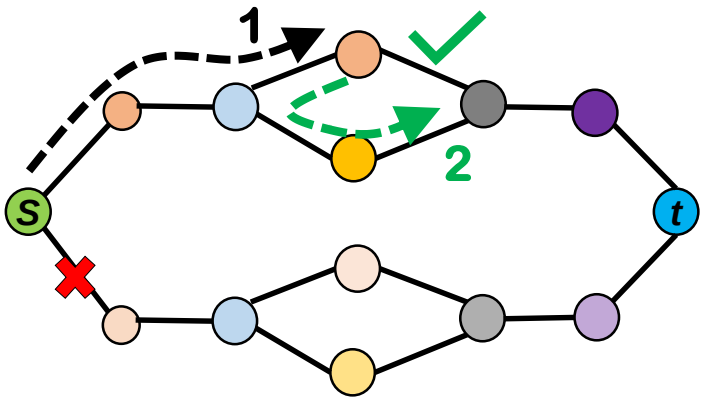

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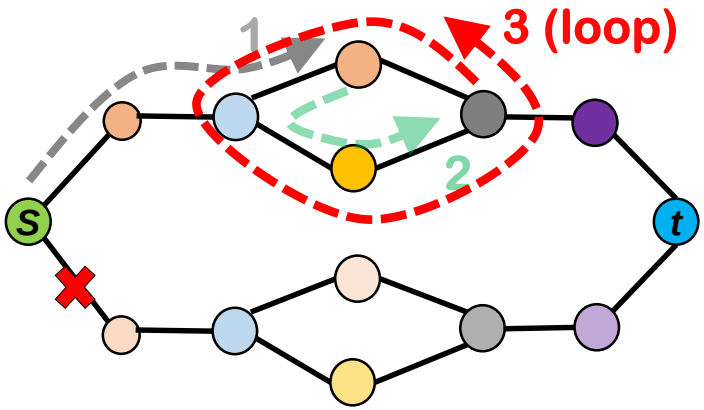
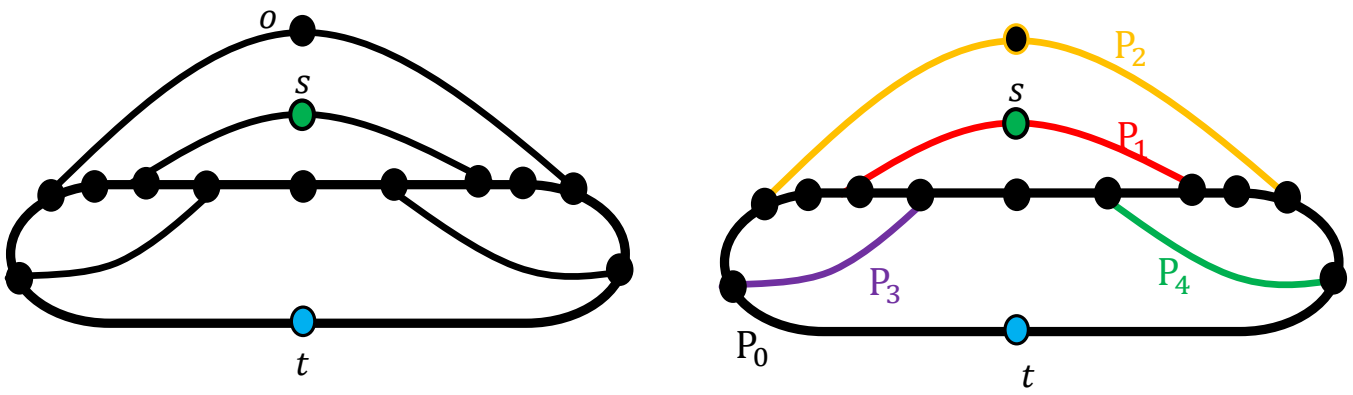


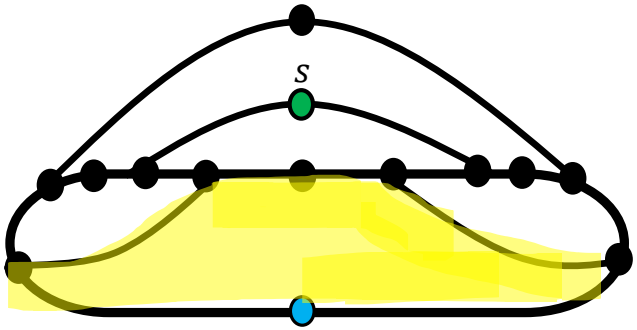
Dynamic 2-Resilient, 2-Bit Rewiriting Algorithm: Via Ear Decomposition

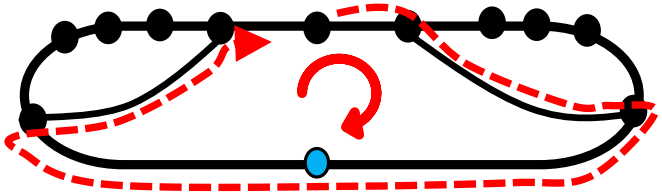
- We can focus on 2-connected graphs wlog
- Ear decomposition of G is a sequence of subgraphs $G = P_0 \cup P_1 \cdots P_k$,
  - P_0 is a cycle including a fixed node (destination) t
  - Each P_i is an ear (path or cycle) with only its endpoints in $P_0 \cup P_1 \cdots P_{i-1}$: endpoints of each ear belong to earlier ears in the sequence but internal vertices of each ear do not



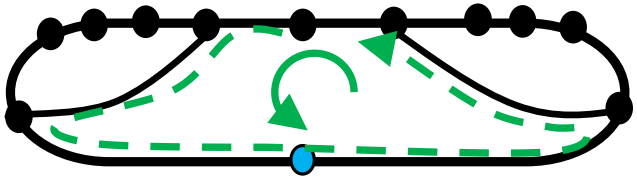
Directed Routing on Faces

- Idea: Can traverse the boundary in the anti-clockwise and clockwise direction (depending on failures)





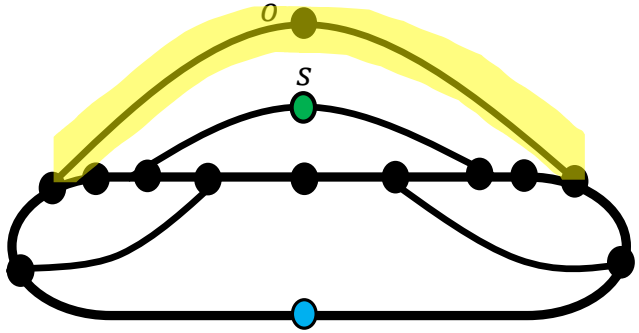
- **Right routing on faces (clockwise)**

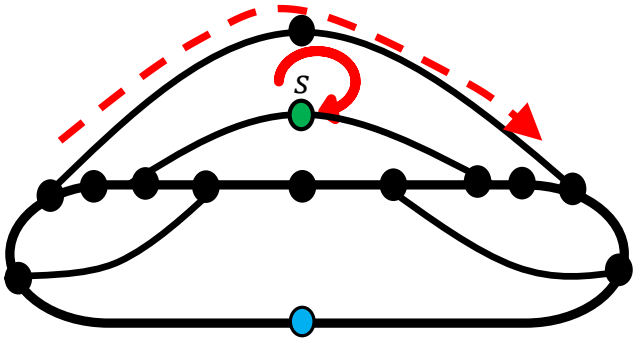


- **left routing on faces (anti-clockwise)**

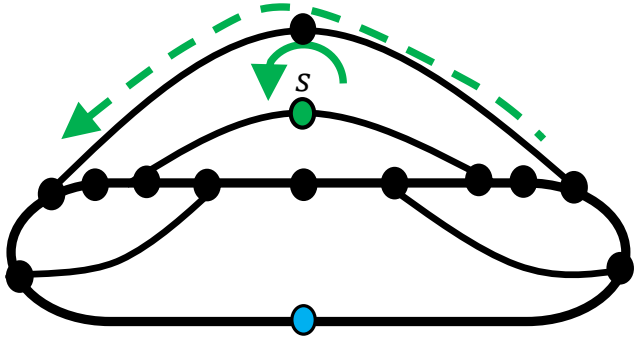
Can do this for each ear...

- For each ear, left/right routing traverse it in anti-clockwise/clockwise direction





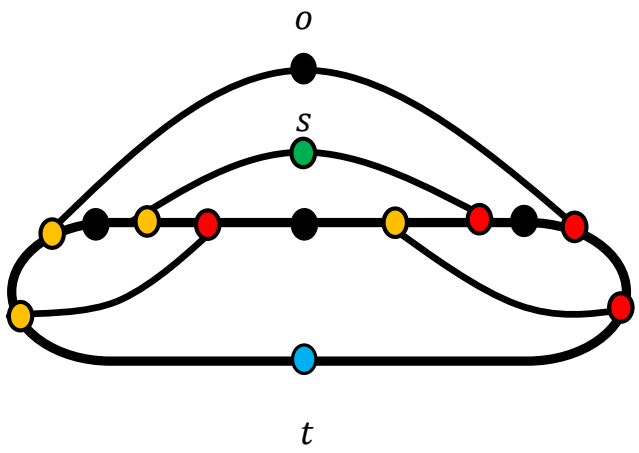
- **Right routing on ears (clockwise)**



- **left routing on ears (anti-clockwise)**

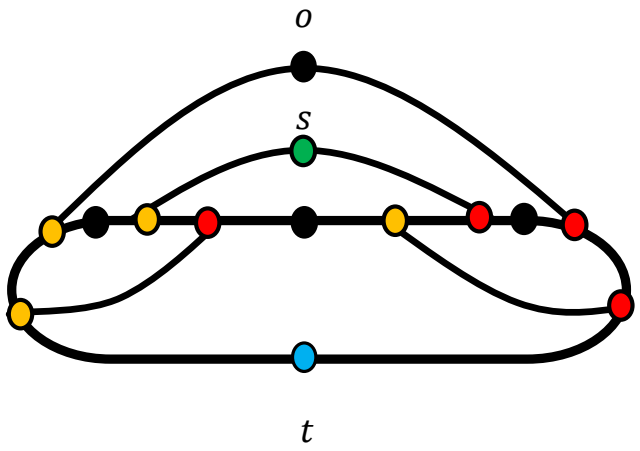
Idea: Precompute important nodes: left/right-most nodes for each phase

- For each face, $\exists P_i$ (ear) that shares common edges
- Precompute: left-most (yellow-colored) and right-most (red-colored)



Idea: Precompute important nodes: left/right-most nodes for each phase

- For each face, $\exists P_i$ (ear) that shares common edges
- Precompute: left-most (yellow-colored) and right-most (red-colored)
- **Complexity:** compute ear-decomposition of $\mathbf{2}$-edge-connected planar graph and left/right routes on ears and faces, left/right-most nodes: time $O(n+m)$ per destination

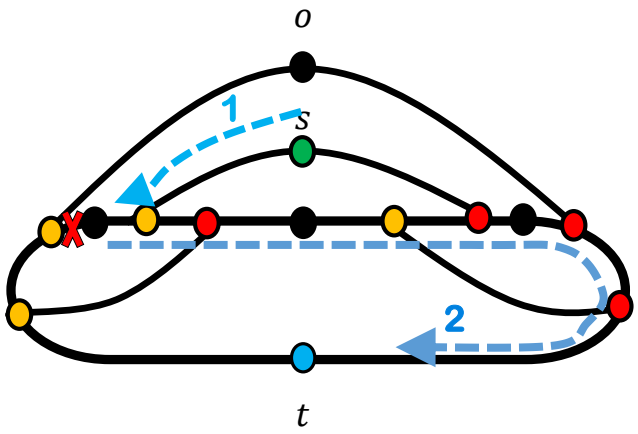


Idea of the algorithm

- Route packets through ears in a "waterfall manner" towards destination. Upon failure, change direction.
- If every ear contains at most one failure, the packet eventually reaches t
- If a second failure occurs on the same ear, routing switches to face-based mode (1 bit) on the adjacent faces
- The algorithm first attempts both directions (now using 1 more bit)
- Will reach a right/left-most node

How to Route by Rewriting One Bit (Ear-Based Routing)

- Starting at the original node, initially $\beta = 0$
- When bit $\beta = 0$, routing on ears,
  - first left and then right direction upon any failure
  - Successful, if seeing ≤ 1 failures for ear-based routing
  -



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- When bit $\beta = 0$, routing on ears,
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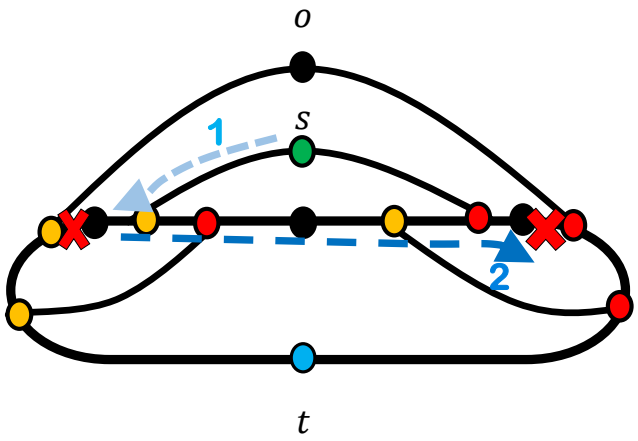
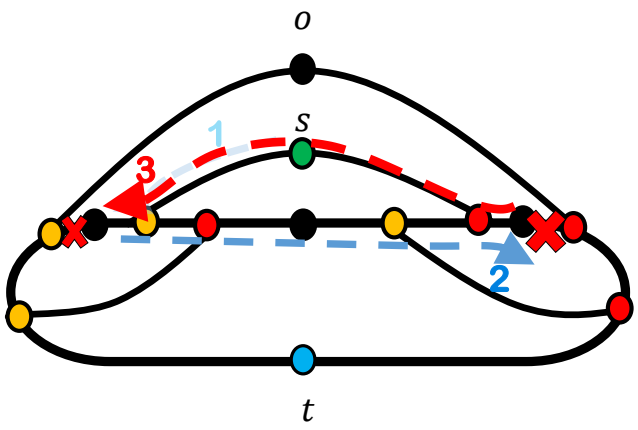
  - Successful, if seeing ≤ 1 failures for ear-based routing
  - Otherwise, when hitting the ***second*** failure, let $\beta = 1$



How to Route by Rewriting One Bit (Face-Based Routing)

- When hitting the ***second*** failure (u, v), $\beta = 1$
- Right routing on the face f_i including (v, u) until stopping the right-most (red) node (->3)
- Otherwise, seeing another failure (a, b) during the right routing on f_i (->3)



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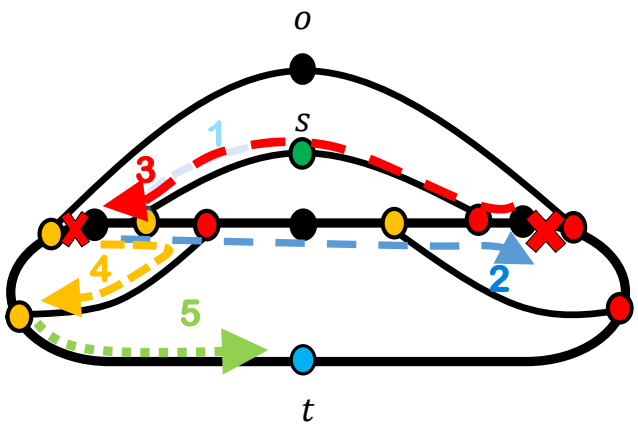
- Otherwise, seeing another failure (a, b) during the right routing on f_i (->3)
- Left routing on the face f_j including (b, a) until stopping the left-most (yellow) node (->4)
- Now, let $\beta = 0$ to restart the ear-based routing (->5), always successful (left/right-most node implies left/right routing on the ear)



Thank you!

Previous results

Our results

Failure type	Per-destination	Per source	Incoming port	Incident links	k-edge-connected graph	Graph Restrictions	Packet rewriting bits	Resiliency	Ref.
static	X		X	X	$k = 2$	planar		No 2-resilient	[Chiesa et al. 2016]
static	X	X	X	X		general		No 3−resilient	[Dai et al. 2023]
static	X	X	X	X		general		≤ 2-resilient	[Dai et al. 2023]
static	X		X	X		general	1 bit	≥ 2-resilient?	Open
static	X	X	X	X		general		≥ 2-resilient?	Open
dynamic	X		X	X	$k = 2$	planar	0	No 2−resilient	[This Talk]
dynamic	X		X	X		general	$\log k$	No k−resilient	[This Talk]
dynamic	X		X	X		planar	1 or 2	≤ 2-resilient	[This Talk]